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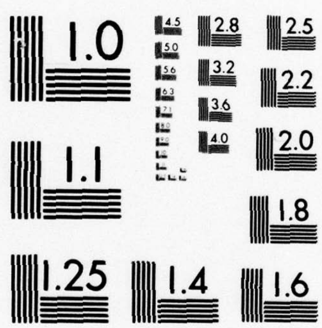

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AN ECONOMETRIC ANALYSIS OF ENROUTE AND TERMINAL AIR TRAFFIC CONTROL

June 1976
FINAL REPORT

U.S. DEPARTMENT OF TRANSPORTATION
Federal Aviation Administration
Office of Aviation Policy
Washington, D.C. 20591

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16. Abstract

This study was undertaken in connection with a comprehensive evaluation of proposed new investments in the upgraded Third Generation Air Traffic Control System. It involved a quantitative analysis of the relationship between ATC system outputs and inputs. Outputs are defined in terms of operations handled while inputs consist of labor and capital. Separate production functions were estimated for enroute (ARTCC) and terminal (tower) control operations. In each case, two different sets of data were used. One consisted of a cross-section of observations on individual facilities in a single year. The other was a time series of annual observations on that portion of the system taken as a whole.

Following development of the production functions, an optimality analysis was conducted. Estimates of the unit cost of labor and capital were developed. These were combined, via a mathematical optimization procedure, with the preferred production functions to compute least-cost combinations of labor and capital for various levels of ATC service demand. The results indicate that, for both centers and towers, substantial additions to the net capital stock will be required over the years to come if expansion of the system (to meet growing service demand) is to be economically efficient.

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SUMMARY

This study was undertaken in connection with a comprehensive evaluation of proposed new investments in the upgraded Third Generation Air Traffic Control System. It involved a quantitative analysis of the relationship between ATC system outputs and inputs. Outputs are defined in terms of operations handled while inputs consist of labor and capital. These relationships, known to economists as production functions, were specified to be of the general form,

$$Q = \alpha_0 L^{\alpha_1} K^{\alpha_2}$$

where Q = output, L = labor, K = capital, and $\alpha_0, \alpha_1, \alpha_2$ = numerical constants (parameters). This form, which has a long history in economic research, is linear in the logarithms of the variables and therefore makes possible relatively straightforward parameter estimation from empirical data. Separate functions were estimated for enroute (ARTCC) and terminal (tower) control operations. In each case, two different sets of data were used. One consisted of a cross-section of observations on individual facilities in a single year. The other was a time series of annual observations on that portion of the system taken as a whole.

The enroute functions, both cross-section and time series, proved highly acceptable on theoretical and statistical grounds, although on occasion the necessity arose to depart from conventional estimation methods. Equal success was realized in estimating tower cross-section functions once the towers were separated into homogeneous sub-groups (Radar Approach, Approach Control and Non-approach

Control). Efforts to develop a time series function for the overall system of towers proved unsuccessful, an outcome which might have been expected in view of the known heterogeneity among towers.

Following development of the production functions, an optimality analysis was conducted. Estimates of the unit costs of labor and capital were developed. These were combined, via a mathematical optimization procedure, with the preferred production functions to compute least-cost combinations of labor and capital for various levels of ATC service demand. The outcome of that analysis suggested that, depending on which of two cost-of-capital concepts is adopted, present labor-capital mixes are either (1) quite efficient; or (2) somewhat overly capital intensive. In either case, the results indicate that for both centers and towers, substantial additions to the net capital stock will be required over the years to come if expansion of the system (to meet growing service demand) is to be economically efficient.

CONTENTS

I. INTRODUCTION

This is the final report of an econometric analysis of enroute and terminal air traffic control (ATC) production functions. The analysis was conducted by Administrative Sciences Corporation (ASC) under a subcontract with J. Watson Noah Associates, Inc. (JWN). That organization was in turn under contract with the U.S. Department of Transportation, Federal Aviation Administration.

This study is part of a comprehensive on-going evaluation of potential costs and benefits associated with new investments in the Upgraded Third Generation Air Traffic Control System (UG3RD). It was an outgrowth of earlier research described in Preliminary Econometric Analysis of Air Traffic Control Production Functions, JWN Report No. FR-117-FAA, June 1975. The purposes of the earlier study were to establish the feasibility of constructing empirical production functions for ATC operations, and to obtain preliminary insights concerning economically efficient mixes of labor and capital. The objectives of the present work were to both refine and extend the previous analysis with a view towards providing input to FAA policy formulation. Certain portions of the earlier report have been reproduced here and other references to it will be included in order for this publication to be completely self-contained.

Following this Introduction, Section II provides background on the theory and application of production functions in the context of air traffic control. Section III describes the various approaches - successful and otherwise -

employed in the development of enroute control functions. Section IV does the same for terminal area (tower) relationships. In Section V, estimates of the annual costs of labor and capital are developed. These are combined in Section VI with the preferred production functions to compute, via a mathematical optimization procedure, least-cost combinations of labor and capital for various levels of ATC service demand. Finally, the major conclusions of the study are presented in Section VII.

II. PRODUCTION FUNCTIONS IN AIR TRAFFIC CONTROL

A. Background

Ferguson defines a production function as ".... a schedule (or table, or mathematical equation) showing the maximum amount of output that can be produced from any specified set of inputs, given the existing technology or 'state of the art.' In short, the production function is a catalogue of output possibilities."[1] This definition is perfectly general and applicable to any type of activity, public or private, where goods or services are turned out in accordance with some organized set of procedures, i.e., a production technology. The concept of a production function as a mathematical equation is the one which will be adopted here since the use of any other concept is impractical.

Production functions are generally thought of as being technical (sometimes called "engineering") relationships and, as such, are only of indirect interest to economists. Economic theory considers these functions part of a set of "givens" which contribute to the determination of 1) levels at which various outputs will be procuced (under optimal conditions); and 2) the rate of utilization and remuneration of the primary factors of production, labor and capital. That research economists do in fact devote considerable attention to the derivation of production functions is explained in large part by necessity. Quantification of the "marginal productivity" of labor and capital in various settings is often essential to the

[1] Ferguson, C.E., Microeconomic Theory, (Homewood, Ill.: Richard D. Irwin, Inc., 1966) p. 110.

resolution of other research questions, and as a practical matter such quantification would otherwise be unavailable. From another point of view, the attempt to provide empirical content to the theoretical notion of production functions is a step in the direction of improving the information base available to economic decision-makers. All else being equal, better information will lead to decisions which increase the efficiency of resource allocation.

This brief bit of background should be sufficient to lay the groundwork for the ensuing analysis. The provision of air traffic control services is a production activity in the classical sense. Direct and indirect labor are combined with capital structures and equipment to provide various quantities and types of services to system users in accordance with a well-defined production technology. A considerable amount of data is available describing the system inputs and outputs, and from that data it should be possible - at least in principle - to estimate the respective contributions, i.e., the marginal products, of the individual inputs. Given this information, meaning given a production function (or functions) for ATC, and given a set of comparable costs for the system inputs, it becomes a straightforward exercise in mathematical optimization to determine least-cost mixes of inputs corresponding to any level of service demand. Such insights, while clearly not sufficient to indicate "the correct" policy decision, should at least sharpen planning for the form in which ATC capacity will grow over time.

B. Cobb-Douglas Functions

As stated earlier, the concept of a production function to be adopted here is that of a mathematical equation. Thus the first issue to be considered is what form the equation will take. Assuming for the moment that output is a function of two inputs, labor and capital, consider the following:

$$Q = \alpha_0 L^{\alpha_1} K^{\alpha_2} \quad . \tag{2.1}$$

where,

$$Q = \text{output}$$
$$L = \text{labor input}$$
$$K = \text{capital input}$$
$$\alpha_0 = \text{a multiplicative constant}$$
α_1, α_2 = "elasticity" coefficients associated with labor and capital respectively

This form, called "Cobb-Douglas" in honor of two of the early investigators of the laws of production,[2] has a number of desirable properties and will constitute the framework for analysis here as it has in a great deal of other econometric research. Note that the relationship is nonlinear and that both inputs are necessary to the production process; i.e., *if either input is zero,* output is zero. The marginal product of either input is defined as the partial derivative of the function with respect to that input:

$$MP_L = \frac{\partial Q}{\partial L} = \alpha_1 \alpha_0 L^{\alpha_1 - 1} K^{\alpha_2} \tag{2.2}$$

$$MP_K = \frac{\partial Q}{\partial K} = \alpha_2 \alpha_0 L^{\alpha_1} K^{\alpha_2 - 1} \tag{2.3}$$

The elasticity of output with respect to either input is:[3]

$$\eta_L = \frac{\partial Q}{\partial L} \cdot \frac{L}{Q} = \alpha_1 \alpha_0 L^{\alpha_1 - 1} K^{\alpha_2} \cdot L / \alpha_0 L^{\alpha_1} K^{\alpha_2} = \alpha_1 \tag{2.4}$$

$$\eta_K = \frac{\partial Q}{\partial K} \cdot \frac{K}{Q} = \alpha_2 \alpha_0 L^{\alpha_1} K^{\alpha_2 - 1} \cdot K / \alpha_0 L^{\alpha_1} K^{\alpha_2} = \alpha_2 \tag{2.5}$$

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[2] Cobb, C.W. and Paul H. Douglas, "A Theory of Production," American Economic Review, Suppl., Vol. XVIII, pp. 139-65.

[3] In economics, if two variables (Y and X) are related, the percentage change in Y divided by the percentage change in X is said to be the elasticity of Y with respect to X. Relatively low elasticities indicate insensitive relations; high ones the opposite.

Thus the Cobb-Douglas function has constant elasticities of output variation with respect to labor or capital input. The marginal rate of substitution of labor for capital, i.e., the rate at which labor may be substituted for capital without changing output levels, is given by:

$$MRS_{L \text{ for } K} = MP_L/MP_K = \frac{\alpha_1 K}{\alpha_2 L} \tag{2.6}$$

Finally, if it is assumed (or if it happens empirically) that $\alpha_1 + \alpha_2 = 1$, the Cobb-Douglas function admits of constant returns to scale. That is, if the levels of both labor and capital are increased by the factor τ, then output increases by the same factor:

$$f(\tau L, \tau K) = \alpha_0(\tau L)^{\alpha_1}(\tau K)^{1-\alpha_1} = \tau\alpha_0 L^{\alpha_1} K^{1-\alpha_1} \tag{2.7}$$

Similarly, if $\alpha_1 + \alpha_2 > 1$, the function shows increasing returns to scale (output increases by more than a factor of τ), and if the coefficients sum to less than unity, decreasing returns (diseconomies of scale) are indicated.

C. Stochastic Specification

The above discussion highlighted theoretical properties of the Cobb-Douglas function which will be used later in the analysis. At this time, in order to prepare for the empirical phase of the work, a slight re-formulation of the basic relationship is required. Equation (2.1) as it presently stands implies that for any specific set of input values, *there corresponds one and only one* output value. Such functions, or models, are often classified as "deterministic". They are fine for theoretical purposes but generally prove inadequate when confronted with real-world data. It is perfectly reasonable to postulate that output levels are determined mainly and systematically by input levels, but observed output may also be affected by non-systematic or random influences. It may be subject to some amount (hopefully

small) of measurement error, and to the combined effects of variables other than labor and capital which behave in no consistent fashion but yet result in a divergence between observed and theoretically expected values of Q. To account for these differences, it has become standard practice to include in econometric models a so-called random error or stochastic disturbance term. The basic Cobb-Douglas function will then be re-written as

$$Q = \alpha_0 L^{\alpha_1} K^{\alpha_2} u \qquad (2.8)$$

where u is considered to be a random variable with a probability distribution having an expected (average) value equal to unity. For any given values of labor and capital, L_* and K_*, the average value of Q will be

$$E(Q) = \alpha_0 L_*^{\alpha_1} K_*^{\alpha_2} \qquad (2.9)$$

but it is recognized that in any particular instance Q may take on values above or below that average. The degree of divergence between the observed and expected values will depend on the size of another parameter in the probability distribution of u, namely its variance.

D. ATC Input Variables

Up to this point the discussion has been both quite general and independent of any data considerations. That orientation will change as the transition between theory and empiricism occurs. It is necessary first to consider precisely what constitutes labor and capital in the context of air traffic control production functions.

1. Labor - There are three types of labor required in the provision of ATC services: direct (controller), indirect (maintenance), and overhead (headquarters and region staffs). There are also two ways in which the labor input may be measured:

in man-years and in annual payroll. Considering these in reverse order, the man-year concept seems preferable to payrolls since production functions are fundamentally technical relationships between physical quantities. In fact, there is a preference in the literature for man-hour rather than wage-earner data whenever it is available.[4]

Concerning the different categories of labor, there are several alternatives available. One would be to include each of the variables individually in the production function. Another would be to aggregate them, and a third choice is that of being selective. In terms of the actual provision of ATC services - particularly the interaction between labor and capital - it would seem that overhead labor could be safely excluded. As for controller and maintenance labor, it may be argued that those activities are separate and equally essential to the production process, and thus the two should be included individually. However, in view of the highly direct ties between maintenance labor and the capital input (maintenance personnel are actually allocated to facilities on the basis of the amount and type of capital in existence), there is some doubt as to whether it is conceptually correct to consider that variable as a separate factor of production, and it is highly unlikely that a meaningful empirical estimate of its contribution to the handling of ATC operations could be obtained. Consequently, the labor input will be defined as direct (controller) man-years. As a part of the optimality analysis, maintenance labor will be included as part of the annualized cost of capital, and overhead costs will be allocated between direct and indirect labor.

2. Capital - The measurement of capital is an extremely difficult concept to handle properly, either theoretically or empirically. First, the ideal measure would be flow of capital services, e.g., machine-hours used, since output and labor input

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[4]See, for example, L.R. Klein, An Introduction to Econometrics, (Englewood Cliffs, N.J.: Prentice-Hall, 1962) p. 98.

are both flow concepts (quantities per unit time). But, as a practical matter that is simply unattainable. The next best approach is to measure the amount of capital stock in existence. (Provided the utilization of existing stock tends to be uniform, this approach is equally acceptable.) Since capital consists of different types of structures and equipment, it is necessary that some aggregation method be adopted. An obvious choice is the dollar value of the stock, and the dollars should of course be converted to a constant price level. Finally, the question arises as to how the physical depreciation and obsolescence of capital should be treated. The choices are to simply consider it negligible or to employ some type of formal depreciation algorithm. The first treatment is neither consistent with reality nor, perhaps for that reason, virtually ever adopted in empirical studies. There are a variety of depreciation algorithms in use, each with its advantages and disadvantages. Selected for use here was an "efficiency" as opposed to "accounting" depreciation schedule.[5] Briefly, this approach represents a compromise between assuming depreciation to be negligible and use of conventional accounting methods.

An analogous situation exists with respect to the categories of capital as existed with the categories of labor. The capital input may be defined in terms of 1) total capital, 2) structures and equipment separately, or 3) structures and the individual types of equipment - communications, data acquisition and other. The choice hinges on two considerations. First, the more variables included in the production function, the more difficult the estimation process will be (due to loss of degrees of freedom and the likelihood of severe multicollinearity, about which more will be said in Section III.) Second, the notion of quantifying the separate contribution of, say, structures and equipment in the real-world provision of ATC services seems conceptually questionable. However, unlike the case of labor where

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[5]For a full discussion, see Capital Stock Measures for Transportation, U.S. Dept. of Transportation, December 1974, Vol. I, pp. 2-7 through 2-9.

one category was direct and the other indirect, no similar distinction exists between different capital inputs and thus the measure that seems best is total capital stock.

E. Output Measures

The preceding sections have made no distinction between enroute and terminal air traffic control. In considering output measures, that differentiation must be clearly drawn. Separate production functions will be developed for enroute services provided by Air Route Traffic Control Centers and for terminal services at ATC Towers. (The operations of Flight Service Stations are not being addressed as part of this study.)

1. Air Route Traffic Control Centers (ARTCC's) - Output of ARTCC's is reported in terms of Departures, Overs and Total Aircraft Handled. A departure is defined as an IFR flight plan filed. An over is an aircraft originating outside the reporting ARTCC area and overflying the area without landing. Total aircraft handled is twice the number of departures (assuming equal numbers of departures and arrivals) plus aircraft overs handled. Each of these categories is further divided into four components: air carrier, air taxi, military and general aviation. A DOT study has recommended that the best overall measure of ARTCC output is a weighted sum of the components of Total Aircraft Handled, with the weights being the reciprocal of the average flying speed of each component.[6] (The adjustment for speed is made to reflect the greater length of time spent under control by a slower than a faster aircraft flying over the same route.) This is an interesting measure - particularly for cost allocation purposes, in which context it was originally developed - but there may be times when an unweighted sum would be more useful. Consequently separate production functions will be estimated using weighted and unweighted measures of total aircraft handled.

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[6] Aviation Cost Allocation Study, Working Paper No. 5: Measures of Use, U.S. Dept. of Transportation, July 1972, p. 55.

2. <u>ATC Towers</u> - The same DOT report referenced in II.E.1. above states (p. 40) that the best measure of the frequency of use of air traffic control tower services is Number of Aircraft Operations. This includes both VFR and IFR operations at the reporting airport plus IFR operations handled for satellite airports. Again this measure reflects services provided to four user groups: air carrier, air taxi, military and general aviation. It is apparent that this overall output measure conceals differences in the duration and quality of services provided various users. One might search for some type of weighting procedure similar to what has been proposed for ARTCC's in an attempt to improve the measure. However, it appears that another approach might be preferable. The universe of ATC towers is a very heterogeneous mixture, and it is unlikely that any type of meaningful production function could be developed for that population taken as a whole. What is probably more useful is to divide the voters into more homogeneous sub-groups. For the purposes of this study, three such groups have been defined: Radar Approach Control, Approach Control, and Non-approach Control. In discussing the production functions developed for each, Section IV also presents information on the size and relative importance of the different groups.

F. <u>Cross-Section vs. Time Series Analysis</u>

For both the ARTCC's and control towers, two entirely different sets of data are available for use in the empirical analysis. The first set consists of observations on output, labor and capital for a sample of individual facilities in a single year (1974). These are the so-called cross-section data. The second set consists of observations on aggregate output, labor and capital for all centers and all towers in each year over a continuous series of years. These time series data necessitate a slight re-specification of the stochastic production function:

$$Q_t = \alpha_0 L_t^{\alpha_1} K_{t-1}^{\alpha_2} u_t \qquad (2.10)$$

Note that the measure of capital stock associated with output in year t is the observation recorded for year t-1. The reason for specifying this one-year lag has to do with the way in which the capital series was compiled. Unlike the cross-section data which was developed from a physical inventory of structures and equipment, this series was built by accumulating annual investment data from budget records. Thus the lag represents delays between purchases and installation of capital, and might also be thought of as reflecting some check-out and training time. Whether one year is precisely the correct lag structure is of course a bit uncertain, but it should serve as an adequate approximation.

Given that both cross-section and time series production functions are to be estimated, what can be said in advance about their characteristics and interpretations? The first and most important point is that they represent two basically different frames of reference. Inferences drawn from the cross-section function pertain to a representative facility, whereas the time series focus is on the system as a whole in a representative year. In short, the former is a micro function and the latter a macro relationship. It is not uncommon for cross-section and time series production studies to produce similar results, but that need not necessarily be so.

In estimation from both types of data, problems arise if the output measures reflect something less that full-capacity levels. The earlier ATC econometric study, to which reference was made in the Introduction, tended to ignore those problems, implicitly assuming that each of the observations represented full-capacity output levels. However, closer inspection of the data have revealed that assumption to be

untenable. Consequently a careful effort has been made to eliminate from the various data bases the less-than-full-capacity observations. The extent to which this was done will be discussed where applicable.

G. Estimation Methods

Although the Cobb-Douglas production function is a nonlinear form, it has the convenient property of being "intrinsically linear". Taking logarithms of each side, the function is seen to be linear in its parameters:

$$\ell nQ = \ell n\alpha_0 + \alpha_1 \ell nL + \alpha_2 \ell nK + \ell nu \tag{2.11}$$

With one minor exception, (2.11) is suitable for estimation by conventional least squares regression.[7] Provided a sufficient amount of independent variation in labor and capital is present in the sample data, estimation can proceed directly. This, unfortunately, is a rather large proviso since labor and capital tend to be closely associated on an empirical basis. If this association - often referred to as inter-correlation or multicollinearity - is very high, conventional least squares estimates of the variables' separate effects can be quite misleading. More specifically, they are subject to large sampling errors, inflated absolute values and incorrect algebraic signs. This situation has been recognized for some time, but only recently has

[7]Recalling that in the original specification the assumption was made that $E(u) = 1$, it follows that $E(\ell nu) \neq 0$, and the disturbance term must have zero expectation for the usual least squares properties to hold. This problem and its remedy are discussed in A.S. Goldgerger, Topics in Regression Analysis, (London: Macmillan, 1968) pp. 120-123. It turns out that the "nuisance parameter", $E(\ell nu)$, can be shown to equal minus one half the variance of ℓnu. Inasmuch as the square of the standard error of estimate (S.E.E.) constitutes an empirical estimate of var(ℓnu), the problem can be overcome by adding one half that quantity to the regression estimate of $\ell n\alpha_0$. In the regression results to be reported later in this section, S.E.E. values will be shown so that this adjustment can be made to the final production function estimates. (Note that this problem has no effect on the estimates of the elasticity coefficients.)

any significant progress been made in the development of methods for combating it. One such method which has a strong theoretical foundation and works well in practice is Hoerl and Kennard's "ridge regression".[8] A description of that procedure is presented in Appendix A. Selective use of it will be made here in an attempt to improve on the least squares estimates where there is evidence of unacceptably high intercorrelation between labor and capital. It is interesting (and reassuring) to note that in a recent article in the economic literature,[9] the use of ridge regression for estimating Cobb-Doublas functions in the presence of collinearity was found to be highly advisable.

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[8]A.E. Hoerl and R.W. Kennard, "Ridge Regression: Biased Estimation for Nonorthogonal Problems" and "Ridge Regression: Applications to Nonorthogonal Problems," <u>Technometrics,</u> Vol. 12, No. 1, February 1970, pp. 55-82.

[9]Brown, Wm. G. and Bruce R. Beattie, "Improving Estimates of Economic Parameters by Use of Ridge Regression with Production Function Application," <u>American Journal of Agricultural Economics</u>, Vol. 57, No. 1, Feb. 1975, pp. 21-32.

III. ENROUTE PRODUCTION FUNCTIONS

By way of brief review, the general form of the production function to be estimated is:

$$Q = \alpha_o L^{\alpha_1} K^{\alpha_2} u \tag{3.1}$$

where

Q = output

L = labor input

K = capital input

α_o = a multiplicative constant

α_1, α_2 = "elasticity" coefficients associated with labor and capital respectively

u = a stochastic disturbance term, assumed to have unitary expectation and to be log-normally distributed

First the cross-section functions will be developed, and attention will then turn to the time series analysis.

A. Cross-Section Model

1. Review of Earlier Results

An important part of the earlier study was the analysis of a cross-section of 23 Air Route Traffic Control Centers (ARTCC's) and their corresponding output, labor and capital measures for FY74. Results of estimating a production function from those data, using the method of least squares, were:

$$\ell n Q = 9.026 + \underset{(10.17)}{1.017 \ell n L} - \underset{(0.60)}{.133 \ell n K} \tag{3.2}$$

$$N = 23$$
$$\bar{R}^2 = .908$$
$$S.E.E. = .183$$
$$F = 109.9$$

where,

Q = total (unweighted) aircraft handled

L = direct (controller) labor in man-years

K = total capital stock, depreciated (thous. of 74$)

Although the overall fit ($\bar{R}^2$) and significance (F) measures were certainly adequate, the estimate of the capital coefficient had an implausible negative sign and a large sampling error (low t-value). This was judged to be a direct consequence of high correlation between labor and capital (.758). The ridge estimation procedure was therefore employed with the following results:

Coef.	Est.	Std. Error	
$\ell n\hat{a}_o$	5.974	—	
$\hat{a}_1$ (Labor)	.684	.055	(3.3)
$\hat{a}_2$ (Capital)	.337	.122	

This was quite a reasonable set of results. The labor and capital coefficients were very close to the respective 2/3 and 1/3 values found in many empirical studies, and the sum of the two indicated very slightly increasing returns to scale. Although t-values for ridge estimates cannot be given the same interpretation as with least squares, it was noted that both estimates were substantially larger than their standard errors.

A second function was estimated from the same data, except that the output measure (total aircraft handled) was broken down into its three components,

i.e., air carrier, general aviation (including air taxi) and military, and each component was weighted by the reciprocal of the average airspeed for that class of aircraft. The weighted components were than summed to produce a new output measure, one recommended by a DOT study to be the best overall measure of ARTCC output.[1] The underlying idea is that the faster the aircraft, the less time it will remain in a region and hence the less enroute control required. Estimation results were:

$$\ell n Q = 2.831 + \underset{(9.59)}{1.080} \ell n L - \underset{(0.55)}{.136} \ell n K \quad (3.4)$$

$$N = 23$$

$$\bar{R}^2 = .899$$

$$S.E.E. = .206$$

$$F = 99.0$$

Inasmuch as these results were very similar to the earlier least squares estimates - and also exhibited the same collinearity symptoms - it was not surprising that the ridge results were equally similar:

Coef.	Est.	Std. Error	
$\ell n \hat{\alpha}_0$	-0.396	—	
$\hat{\alpha}_1$ (Labor)	.727	.062	(3.5)
$\hat{\alpha}_2$ (Capital)	.361	.137	

The same remarks concerning the a priori reasonableness of the first set of ridge results also apply to those above.

2. Alternative Weighting Schemes

Despite the generally favorable outcome resulting from the use of the speed-reciprocal weights, there are two possible concerns associated with those

[1] Aviation Cost Allocation Study, Working Paper No. 5: Measures of Use, U.S. Dept. of Transportation, July 1972, p. 55.

results. One is that while those weights take into account the duration of control required of a center, they do not consider intensity of control. The other is that since the ARTCC's tend to be a homogeneous set of facilities, the labor, capital and output data may behave the same regardless of the type of weighting scheme employed. Further analysis was therefore conducted to gain insights into those issues.

One of the products of the Cost Allocation Study referenced earlier was a set of long-run ARTCC marginal costs applicable to air carrier, general aviation and military aircraft. There were actually two sets of costs developed, one relating to operations and maintenance (O&M) and the other to facilities and equipment (F&E). They are shown in the table below.

ARTCC LONG-RUN MARGINAL COSTS

	Air Carrier	Gen. Aviation	Military
O&M	$10.31	$ 1.38	$ 9.19
F&E	17.66	0.00	36.07

Units: Per Aircraft Handled

Source: Airport and Airway Cost Allocation Study, Part 1: Technical Supplement, U.S. Dept. of Transportation, November 1973, p.109.

Three separate production functions were estimated with these costs applied as weights. The first used only O&M costs; the second only F&E; and in the third an average of the two was used. Results were:

Weights: O&M Marginal Costs

$$\text{(Least Squares)} \quad \ell nQ = 9.994 + \underset{(2.57)}{.739 \ell nL} - \underset{(0.17)}{.107 \ell nK} \tag{3.6}$$

$N = 23$

$\bar{R}^2 = .354$

S.E.E. = .525

$F = 7.03$

(Ridge) Coef.	Est.	Std. Error	
$\ell n\hat{a}_0$	7.745	—	
$\hat{a}_1$ (Labor)	.496	.159	(3.7)
$\hat{a}_2$ (Capital)	.237	.348	

Weights: F&E Marginal Costs

$$\text{(Least Squares)} \quad \ell nQ = 9.451 + \underset{(1.72)}{.374 \ell nL} + \underset{(0.25)}{.120 \ell nK} \tag{3.8}$$

$N = 23$

$\bar{R}^2 = .233$

S.E.E. = .397

$F = 4.34$

(Ridge) Coef.	Est.	Std. Error	
$\ell n\hat{a}_0$	8.811	—	
$\hat{a}_1$ (Labor)	.266	.120	(3.9)
$\hat{a}_2$ (Capital)	.239	.263	

Weights: Ave. of O&M and F&E Marginal Costs

(Least Squares) $$\ell n Q = 8.006 + \underset{(7.03)}{.836\ell n L} + \underset{(0.03)}{.008\ell n K} \quad (3.10)$$

$N = 23$

$\bar{R}^2 = .839$

$S.E.E. = .217$

$F = 58.4$

(Ridge)

Coef.	Est.	Std. Error
$\ell n\hat{a}_0$	5.834	—
$\hat{a}_1$ (Labor)	.572	.066
$\hat{a}_2$ (Capital)	.357	.144

(3.11)

Interpretation of the above results seems fairly straightforward. Neither the O&M nor F&E marginal costs perform very well individually as a set of weights, thereby discounting the earlier suggestion that the data may be insensitive to any weighting scheme, and by implication assigning more credence to the speed-reciprocal weights. The average of the two sets of costs performs surprisingly well, but in terms of the Least Squares summary statistics ($\bar{R}^2$ and F) and the substantial diseconomies of scale suggested by the ridge estimates ($\hat{a}_1 + \hat{a}_2 = .929$), it seems fair to conclude that both the unweighted and speed-reciprocal weighted functions are preferable to this one.

3. Alternative Output Measures

Two additional lines of inquiry involving new output measures were pursued in an effort to see if refinements might be made to the enroute cross-section function. The first required continued use of the three components of total aircraft handled. Output for center "i" was defined as:

$$Q_i = C_i + M_i + G_i + \sqrt{C_i G_i} + \sqrt{M_i G_i} \quad (3.12)$$

where

C = carrier aircraft handled

M = military aircraft handled

G = general aviation (including taxi) aircraft handled

The sum of the first three terms, $C_i + M_i + G_i$, is simply total aircraft handled as previously used. The rationale underlying the fourth and fifth terms is the suggestion in the ATC literature that maximum demands are placed on the control process when slow (general aviation) and fast (carrier and military) aircraft must be dealt with simultaneously. While the data available for this study do not reveal anything directly about the simultaneous presence of the different categories of aircraft, it seems reasonable to assume that centers having the greatest balance between slow and fast aircraft (as quantified by the products C_iG_i and M_iG_i) will have the greatest requirements for simultaneous control. The sum of the first three terms might be considered to be the "scale" factor, while the final two represent the "interactive" factor. Square-roots of the fourth and fifth terms were taken so that the sums of those two numbers would not dwarf the measure of total aircraft handled. Results of estimating this function were:

$$\text{(Least Squares)} \quad \ell n Q = 8.425 + \underset{(8.97)}{1.021 \ell n L} - \underset{(0.15)}{.038 \ell n K} \quad (3.13)$$

$$N = 23$$

$$\bar{R}^2 = .892$$

$$S.E.E. = .208$$

$$F = 92.1$$

(Ridge) Coef.	Est.	Std. Error	
$\ell n\hat{a}_o$	5.638	—	
$\hat{a}_1$ (Labor)	.694	.063	(3.14)
$\hat{a}_2$ (Capital)	.403	.138	

In terms of statistical quality and a priori reasonableness, these results are very comparable to the unweighted and speed-reciprocal functions. It is interesting to note the increased value of the coefficient associated with capital (.403 as compared with the earlier values of .337 and .361) as well as the fairly significant economies of scale estimated to exist ($\hat{a}_1 + \hat{a}_2 = 1.097$).

The final cross-section enroute function to be estimated involved the use of an entirely different measure of output: potential conflicts avoided. This measure, which is an analytic construct in the sense that the actual numerical values are meaningful only in relation to one another, was available for only 18 of the original 23 ARTCC's. In the reduced sample there was virtually no correlation between labor and capital, thus negating the need for ridge estimation. Least squares results were:

$$\ell nQ = -10.293 + \underset{(3.65)}{2.525\ell nL} + \underset{(0.14)}{.171\ell nK} \qquad (3.15)$$

$$N = 18$$
$$\bar{R}^2 = .400$$
$$S.E.E. = .581$$
$$F = 6.68$$

As an output measure in a production function, "potential conflicts avoided" does not seem very useful, although it does appear to be highly responsive to variations in the labor (controller) input.

B. Time Series Model

1. Review of Earlier Results

A time series function of the general form described in Section II.F.,

$$Q_t = \alpha_o L_t^{\alpha_1} K_{t-1}^{\alpha_2} u_t \tag{3.16}$$

where,

Q = total aircraft handled (in thous.)

L = total direct (controller) labor, in man-years

K = otal capital stock, depreciated (thous. of 74$)

t = year of the observation

was estimated with the following results:

$$\ell n Q_t = 0.148 + \underset{(5.19)}{.658 \ell n L_t} + \underset{(1.96)}{.270 \ell n K_{t-1}} \tag{3.17}$$

where,

N = 29

$\bar{R}^2$ = .943

S.E.E. = .193

F = 233.6

D.W. = 0.429

On the whole, these results bore a good deal of similarity with the ridge cross-section estimates, although the capital elasticity estimate ($\hat{\alpha}_2$) was somewhat lower than before, and together the labor and capital estimates suggest decreasing returns to scale over time.[2] This latter finding was not altogether plausible, and a more fundamental concern over the function as specified and estimated above

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[2]Something of an additional problem was the fact that the low Durbin-Watson (D.W.) statistic is indicative of positive autocorrelation, a condition for which certain re-specification and re-estimation procedures are sometimes recommended. However, since the consequences of autocorrelation do not bear on parameter estimation as such, which is the main concern here, no further attention was paid to this matter.

is the implicit assumption of constant technology throughout the period. With these considerations in mind, further analysis was undertaken in an effort to improve the time series formulation.

2. Modified Data Base

With reference to the discussion in Section II.A concerning the estimation difficulties that can arise if some of the observations reflect less than full-capacity output measures, it was speculated that the estimates of the time series function might be affected by that problem. A year-by-year inspection of the series revealed several years (actually several periods of years) that were clearly in the "less than full-capacity" category; i.e., output was declining while labor and capital remained constant, or output was constant while labor and/or capital increased. It was apparent that the following years should be eliminated: 1948-53, 1959-66, 1970-71 and 1974. Accordingly, the data base was modified by removing those years, and the period 1972-73 was also considered for possible elimination.[3] The time series function was re-estimated twice, first with and next without, 1972-1973. Results were:

$$\ell n Q_t = 1.165 + \underset{(9.37)}{.783}\ell n L_t + \underset{(1.44)}{.124}\ell n K_{t-1} \qquad (3.18)$$

$$N = 12 \text{ (including 1972-73)}$$

$$\bar{R}^2 = .990$$

$$S.E.E. = .081$$

$$F = 579.17$$

$$D.W. = 1.58$$

[3]The problem with the early 1970's was that capital expansion plans were made in connection with a major study in 1969 and based on forecasts developed in that time frame. The forecasts later proved to be too high, resulting in capital utilization at less than full-capacity.

and,

$$\ell n Q_t = .516 + \underset{(10.69)}{.756 \ell n L_t} + \underset{(2.49)}{.195 \ell n K_{t-1}} \qquad (3.19)$$

N = 10 (excluding 1972-73)

$\bar{R}^2$ = .986

S.E.E. = .071

F = 253.7

D.W. = 1.70

The labor estimate in (2.19) is suspiciously high and the capital estimate suspiciously low. (See footnote # 3 for discussion pertinent to this.) Therefore the set of observations with 1972-73 removed was considered preferable. Note that the elasticity estimates from those data still reflect a fairly high degree of diminishing returns. Recalling the rather favorable results obtained in the cross-section analysis when output was measured in terms of both "scale" and "interactive" factors, it was decided to examine that same concept with the time series function.[4] Results were:

$$\ell n Q_t = -.218 + \underset{(5.81)}{.681 \ell n L_t} + \underset{(3.14)}{.328 \ell n K_{t-1}} \qquad (3.20)$$

N = 8

$\bar{R}^2$ = .987

S.E.E. = .077

F = 258.4

D.W. = 1.90

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[4]This presented something of a data problem since the series on total aircraft handled (by type of aircraft) only begins in 1957. It turns out that the distribution by type aircraft was essentially constant for 1957-59, and so that distribution was applied to 1954-56 in order to distribute the totals for those years. Observations prior to 1954 were simply eliminated.

This is the most reasonable time series function obtained yet. It admits of slightly increasing return to scale ($\hat{\alpha}_1 + \hat{\alpha}_2 = 1.009$), and the capital coefficient is very close to the estimate generated in the cross-section analysis. Further, the t-values and other summary statistics are as good or better than the earlier ones. Consequently, the present scale/interactive concept of output (as well as the present data base) was retained for the subsequent analysis which sought to take into account the effects of technological change.

3. Models Incorporating Technological Change[5]

There is reason to believe that technological progress in air traffic control has taken place over the period of years covered by the time series data. In the context of economic analysis, this means that increased output should be obtainable with the same quantities of inputs employed before the progress occurred; or, conversely, fewer inputs should be required to produce the previous levels of output. Attempts to quantify those effects within the framework of a Cobb-Douglas production function usually take the form of adjustments to the multiplicative constant terms. If progress is assumed to take place continuously, then a time variable (with an associated coefficient) is introduced into the function. This permits α_o to change at a constant rate. If, on the other hand, progress occurs over discrete periods, dichotomous or "dummy" variables are included and α_o assumes a new level with each period of change. Both approaches were examined here. First, with a continous time variable, estimation results were:

$$\ell n Q_t = \underset{}{4.186} + \underset{(5.08)}{.101T} + \underset{(6.10)}{.425\ell n L_t} - \underset{(2.46)}{.341\ell n K_{t-1}} \qquad (3.21)$$

[5]A useful reference on this topic is Lester B. Lave, Technological Change: Its Conception and Measurement, (Englewood Cliffs, N.J.: Prentice-Hall, 1963).

$$N = 8$$
$$\bar{R}^2 = .998$$
$$S.E.E. = .032$$
$$F = 1036.3$$
$$D.W. = 3.13$$

The negative sign on the capital coefficient indicates what might certainly have been expected; i.e., the time variable introduces a great deal of multicollinearity. It was also to be expected that the ridge procedure would correct that problem, although the final ridge estimates were not very satisfactory:

Coef.	Est.	Std. Error	
$\ell n\hat{\alpha}_o$	1.276	—	
$\hat{\alpha}_1$ (Labor)	.412	.019	(3.22)
$\hat{\alpha}_2$ (Capital)	.222	.013	
$\hat{\alpha}_3$ (Time)	.034	.001	

The second approach involved the introduction of a dummy variable (denoted by δ) with a value of one for the sample years in which "third generation" ATC technology was in effect (1967-69), and zero otherwise. Estimation results were:

$$\ell nQ_t = 5.617 + \underset{(2.28)}{.655\delta} + \underset{(7.85)}{.806\ell nL_t} - \underset{(0.91)}{.237\ell nK_{t-1}} \quad (3.23)$$

$$N = 8$$
$$\bar{R}^2 = .993$$
$$S.E.E. = .057$$
$$F = 317.8$$
$$D.W. = 2.36$$

Again the presence of a third variable increased the overall level of collinearity, inflating the labor estimate and producing a negative sign on the estimate of capital's contribution. Again the ridge procedure corrected these basic flaws:

Coef.	Est.	Std. Error	
$\ln\hat{\alpha}_0$	2.377	—	
$\hat{\alpha}_1$ (Labor)	.491	.036	(3.24)
$\hat{\alpha}_2$ (Capital)	.236	.018	
$\hat{\alpha}_3$ (Tech. Dummy)	.301	.036	

However, the resultant labor and capital estimates are simply too low to be either plausible or useful for forecasting purposes. Thus we conclude that within the limits of the data and analytic framework employed in this study, it is not possible to explicitly and adequately account for inter-temporal changes in ATC technology.

As something of a postscript to this section, another function was estimated from a set of observations which included the years 1972-73, and a dummy variable was defined to have a value of one for those years and zero otherwise. Results were:

$$\ln Q_t = -.239 - \underset{(1.75)}{.129\delta} + \underset{(6.28)}{.675\ln L_t} + \underset{(1.75)}{.333\ln K_{t-1}} \quad (3.25)$$

$$N = 10$$

$$\bar{R}^2 = .990$$

$$S.E.E. = .072$$

$$F = 302.2$$

$$D.W. = 1.89$$

These results tend to validate the rationale given earlier for excluding 1972-73. The negative coefficient (with a reasonably high t-value) associated with the dummy suggests that those years indeed lie below the plane of the others, and that when this is explicitly recognized (accounted for in the model), the labor and capital elasticity estimates are virtually unaffected by the inclusion of those points.

IV. TOWER PRODUCTION FUNCTIONS

In the earlier study, very few useful results emerged from either the cross-section or time series analysis of terminal (tower) operations. The conclusion was drawn that the basic difficulty stems from the fact that the universe of ATC towers consists of a very heterogeneous set of facilities. In order to deal with this problem, it was decided that, at least in the cross-section analysis, the towers could be categorized into more homogeneous and meaningful sub-groups. Separate production functions would then be developed for each. Insofar as the time series analysis was concerned, it was considered doubtful that the "system" of ATC towers would exhibit any economically meaningful input-output relationships.

A. Cross-Section Functions

1. Radar Approach Control

a. Output Measure: Aircraft Operations

The first sub-group of towers examined are those classified as "Radar Approach Control." Out of the total of 438 towers reported for FY74 in the time series data, approximately 36% are in this category. These radar appraoch (RA) towers tend to be considerably larger than the other types, accounting for approximately 69% of total tower controller man-years.[1]

From the earlier study, a sample of 13 RA towers was available for analysis.[2] Defining output as the sum of total operations, secondary instrument opera-

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[1]These statistics were compiled from computer print-outs and staffing reports supplied by the FAA.

[2]The sample actually consisted of 14 towers, but JFK International was eliminated. The problem with that facility is that its ATC operations are augmented by the New York Common Room (CIFFR), resulting in a smaller controller labor requirement than it would otherwise have.

tions and overs, the following production function was estimated:

$$\ell nQ = 6.141 + \underset{(6.7)}{.780\ell nL} + \underset{(2.2)}{.380\ell nK} \quad (4.1)$$

$$N = 13$$

$$\bar{R}^2 = .875$$

$$S.E.E. = .217$$

$$F = 42.9$$

From a statistical point of view, this is a very satisfactory relationship. From an economic point of view, there is some question as to whether the indication of substantial scale economies ($\hat{\alpha}_1 + \hat{\alpha}_2 = 1.160$) is reliable. In assessing this issue, it should be noted that the sample includes considerable variability in the sizes of towers. At the lower end is Wilkes-Barre, Pa. with 19 controller man-years, \$3.2 million in capital and 94.5 thousand units of output (as previously defined). At the other extreme is Chicago (O'Hare) with 145 man-years of labor, \$11.3 million in capital and output of 806.6 thousand. Over such a range, it may well be that increasing returns to scale do exist. However, considering it important to pursue that issue further, an additional 12 RA towers were selected in the same manner as the first set and added to the data base. Re-estimation of the function produced the following:

$$\ell nQ = 5.903 + \underset{(9.5)}{.737\ell nL} + \underset{(3.2)}{.425\ell nK} \quad (4.2)$$

$$N = 25$$

$$\bar{R}^2 = .837$$

$$S.E.E. = .199$$

$$F = 62.5$$

The function appears to be highly stable and quite satisfactory. Again, however, because of the importance of this class of towers, a decision was made to examine

an alternative measure of output.

b. <u>Output Measure: Runway Acceptance Rates</u>

For the nation's thirty largest terminal facilities, data on "runway acceptance rates" were obtained. These data report the maximum number of aircraft operations that can be handled at each facility per hour, with VFR and IFR ops given separately. On the surface this would appear to be an attractive output measure for a production function since it attempts to capture a facility's "full-capacity" operating level. However, the difficulty with acceptance rates is that they relate to peak period operations which may be reached several times, a few times or not at all on an average day at any given facility. They are, in a sense, "theoretical" quantities while the corresponding labor and capital data tend to reflect actual levels of utilization. Also, the acceptance rates vary over a range of approximately 50 to 130, which is considerably less than that of the previous output measure. These difficulties were manifested in the estimation results. First, for IFR acceptance rates:

$$\ell nQ = 1.198 + \underset{(1.92)}{.276\ell nL} + \underset{(1.28)}{.213\ell nK} \qquad (4.3)$$

$$N = 30$$

$$\bar{R}^2 = .280$$

$$S.E.E. = .237$$

$$F = 6.64$$

and, for VFR rates:

$$\ell nQ = 2.040 + \underset{(.139)}{.224\ell nL} + \underset{(0.94)}{.174\ell nK} \qquad (4.4)$$

$$N = 30$$

$$\bar{R}^2 = .148$$

$$S.E.E. = .266$$

$$F = 3.51$$

Because of the clear superiority of the previous output measure, no further analysis of runway acceptance rates was conducted.

2. Approach Control Towers

The second sub-category examined consisted of towers classified as "Approach Control." That group represents approximately 15% of the total of 438 towers, and slightly less than 9% of the 10,233 man-years of controller labor. An attempt was made to estimate a production function from the available sample of AC towers, using the same output measure as in IV. A.1.a, with the following results:

$$\ell nQ = 10.458 + \underset{(4.22)}{1.064\ell nL} - \underset{(0.63)}{.262\ell nK} \qquad (4.5)$$

$$N = 11$$
$$\bar{R}^2 = .638$$
$$S.E.E. = .184$$
$$F = 9.80$$

This is obviously not a very satisfactory function, and the negative capital coefficient is not attributable to collinearity between labor and capital. One of the problems is the rather small amount of sample variability in both the input and output measures. Labor ranges from a low of 10 man-years to a high of 22, and capital from $1.080 million to $1.748 million. Output runs from 55,418 to 145,213. This, coupled with the fairly small proportion of towers and resources represented by the AC class, raises the question of whether a separate function is either feasible or desirable. It was thus decided to examine the effects of pooling the AC observations with the RA data set. Two new functions were then estimated, one with the combined 36 observations, and the other including a dummy variable set equal to one for the AC towers and

zero for the RA's. Results were:

$$\ell nQ = 8.551 + \underset{(9.4)}{.723\ell nL} + \underset{(1.3)}{.117\ell nK} \quad (4.6)$$

$N = 36$

$\bar{R}^2 = .863$

$S.E.E. = .216$

$F = 111.2$

The change in the capital coefficient from its value of .418 in Eq. (4.2) makes it clear that pooling is not to be recommended. When the function with the dummy variable was estimated, the outcome was substantially different:

$$\ell nQ = 6.372 + \underset{(2.4)}{.404\delta} + \underset{(10.3)}{.775\ell nL} + \underset{(2.8)}{.352\ell nK} \quad (4.7)$$

$N = 36$

$\bar{R}^2 = .881$

$S.E.E. = .202$

$F = 87.2$

As a production function for the AC class, the above is quite reasonable. The higher-than-usual productivity of labor vis-a-vis capital is consistent with what emerged from the AC sample alone, and the .352 coefficient for capital is certainly plausible, as are the very slight economies of scale. The positive coefficient on the dummy variable, increasing the value of δ_0, says that a higher level of output will be produced in AC towers with a given level of capital and labor than in RA's. This is logical since the RA's handle a high percentage of instrument operations which require more labor and capital than VFR ops. The above function is therefore recommended for use with Approach Control towers, although

the function developed originally for the Radar Approach sub-group will be retained for that class.

3. Non-Approach Control Towers

This final group represents nearly half (48.8%) of all towers in existence, but less than one-fourth (22.8%) of total controller labor. They are, in short, the small and relatively unsophisticated facilities. From an analytic point of view, the problem with "smallness" is, first, there are certain minimum levels or "fixed costs" of labor and capital required for any tower to operate. Output will be observed to vary - say from 20,000 to 50,000 operations per year - without any meaningful variation in those fixed levels of inputs. Then, as the inputs do increase; e.g., from 8 controllers to 12, or from $.8 million in capital to $1.2 million, output may double or triple. These assertions are borne out very clearly in the data. First, from a sample of 13 NA towers, with output measured in terms of total operations (secondary instrument ops and overs are irrelevant here), the production function estimates were:

$$\ell n Q = -0.132 + \underset{(3.0)}{1.978\ell n L} + \underset{(2.4)}{1.049\ell n K} \qquad (4.8)$$

$$N = 13$$

$$\bar{R}^2 = .535$$

$$S.E.E. = .515$$

$$F = 7.9$$

The fit is not particularly good, as intimated earlier, and the returns to scale are very, very large. When the set of towers with less than 45,000 operations per year was eliminated from the data base and the function re-estimated, the results were:

$$\ell n Q = 3.676 + \underset{(4.6)}{1.686\ell n L} + \underset{(2.6)}{.613\ell n K} \qquad (4.9)$$

$$N = 9$$
$$\bar{R}^2 = .768$$
$$S.E.E. = .246$$
$$F = 14.2$$

Although it may seem a bit irregular, this function probably describes quite accurately the relationship between output, labor and capital for the NA facilities. The "noise" at the bottom end of the spectrum has been removed, the productivity of labor relative to capital parallels a wide variety of other findings, and the substantial returns to scale ($\hat{a}_1 + \hat{a}_2 = 2.299$) are, for reasons given earlier, almost certainly consistent with the realities of this class of towers.

B. Time Series Function

The FAA has compiled the same type of time series data on total labor, capital and output for towers as for centers. With regard to model sepcification, the one-year capital lag discussed earlier is also appropriate here. Results of estimating the function for the period 1947-1974 were:

$$\ell n Q_t = 4.517 + \underset{(1.66)}{.194 \ell n L_t} + \underset{(4.17)}{.360 \ell n K_{t-1}} \tag{4.10}$$

$$N = 28$$
$$\bar{R}^2 = .914$$
$$S.E.E. = .140$$
$$D.W. = 0.43$$
$$F = 145.1$$

where Q_t is measured in thousands of total operations. The defects in this function are readily apparent. They stem from, among other things, the fact that the function seems to have shifted considerably over time. When it was estimated for the period 1947-1958, the outcome (ignoring the summary statistics) was:

$$\ell nQ_t = 10.77 + \underset{(8.06)}{.636\ell nL_t} - \underset{(3.90)}{.543\ell nK_{t-1}} \qquad (4.11)$$

and for 1959-1969, it changed to:

$$\ell nQ_t = 5.23 - \underset{(0.82)}{.512\ell nL_t} + \underset{(4.76)}{.814\ell nK_{t-1}} \qquad (4.12)$$

As with the center data, several of the years in the tower series show output levels at less than full-capacity. To examine the possibility that this might be the major source of difficulty, these years were eliminated: 1949-54, 1959-65, and 1970-74. Re-estimation produced the following:

$$\ell nQ_t = 4.552 + \underset{(2.53)}{.254\ell nL_t} + \underset{(4.62)}{.327\ell nK_{t-1}} \qquad (4.13)$$

$N = 10$

$\bar{R}^2 = .974$

S.E.E. = .077

D.W. = 1.48

F = 167.6

It is apparent that nothing very satisfactory is going to emerge from the time series data. As was revealed in the cross-section analysis, the universe of towers consists of several distinctive sub-groups with different production functions applicable to each. And, an "operation handled" for a Radar Approach tower is quite different in terms of its labor and capital requirements than one at a Non-Approach Control facility. If time series data were available for each of the sub-groups separately, it is quite likely that satisfactory production functions could be developed. Lacking those data, it will be necessary to rely on the cross-section functions exclusively in the least-cost analysis.

V. INPUT COST ANALYSIS

The purpose of this section is to develop estimates of the annual costs of labor and capital for both enroute and terminal facilities. The resultant estimates will be employed in Section VI to determine least-cost input combinations. These estimates differ significantly from those presented in Preliminary Econometric Analysis of Air Traffic Control Production Functions. The revisions are in part a result of new data becoming available but mainly they reflect an extensive reassessment of the underlying concepts and relevance of costs as used in this analysis.

A. Labor Input Costs

The first requirement is to estimate the annual cost of a man-year of direct (controller) labor for both centers and towers. Those estimates can be obtained directly from appropriations data for FY74:[1]

Center labor (w_{ζ}) = \$22,286

Tower labor (w_{τ}) = \$20,888

B. Capital Input Costs: General

Obtaining estimates of the annual cost of a unit (dollar) of capital poses both conceptual and empirical problems.

A fundamental difference between the cost of labor and the cost of capital is that the former is explicit and the latter implicit. One approach to the estimation of capital costs, which has its basis in traditional micro-

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[1]The source of this data is the Federal Aviation Administration FY1975 Budget Estimates Submitted to Congress.

economic theory, is to imagine that the capital is in fact privately owned, and to then inquire as to its annual rental price. The "owner" would (under competitive conditions) rent a unit of capital for a price which permits him to cover all costs of ownership, i.e., depreciation, maintenance and the normal return available to his particular type of capital. The next step in this line of reasoning is to put the Government in the place of the private owner. It follows that the implicit cost to the Government is the same as the explicit rental price the private owner would charge in a normal market transaction. That price, then, is said to be the "true" annual cost of a unit of capital.

Assuming this reasoning is conceptually sound, the problems of quantifying depreciation, maintenance, and "normal return" are nonetheless formidable. And, to further complicate matters, there is an alternative line of reasoning which deserves consideration. Imagine for a moment that the structures and equipment heretofore called "capital" had useful lives of exactly one year rather than the several years which they in fact have. How would that change things? Depreciation is still a proper cost element for inclusion, and its computation is actually simplified. The assets having no economic value at the end of the year, the correct depreciation charge is simply their original acquisition cost. Similarly, the cost of maintenance continues to be relevant, and its computation on an annual basis is independent of the useful lives of structures and equipment. So far, nothing substantive has changed. What about the third cost element: "normal return to capital"? Is such a charge still appropriate? The point, or issue, being raised is whether the simple multi-year durability of structure and equipment creates an illusion of "capital" as conceived in neoclassical economics, and in turn leads to an improper conceptualization of the

attendant costs. By the mere act of hypothetically shortening the assets' useful lives, that illusion is either partly or wholly dispelled.

To consider the matter from another (but closely analogous) perspective, what if the focus of the analysis were on trade-offs between personnel and hardware in some defense context? Are runways, hangars, radars and aircraft "capital" to which a "rate of return" should be imputed, or are they simply durable public goods whose costs cannot be conveniently expressed on an annualized basis? Current practice in the defense establishment favors the latter interpretation.

It is important that the discussion here not be confused with discussions of "discounting" and "discount rates."[2] Those discussions, which relate equally to all types of economic resources, are concerned with benefits which society foregoes when resources are transferred from the private to the public sector. In particular, the notion of discounting is concerned with the intertemporal effects of such transfers. Our concern here, couched in a purely static framework, is whether the Government's ownership and use of one type of resource (durable structures and equipment) entails an annual "opportunity cost of capital" which has no analogue in the use of another type of resource, direct labor.

The thrust of the foregoing paragraphs is that the following capital cost estimates will of necessity be subject to both conceptual and empirical

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[2]For more background on these topics, see, for example, W.J. Baumol, "On the Social Rate of Discount," The American Economic Review, Vol. LVIII, No. 4, June 1968, pp. 788-802. Perhaps the most recent contribution to this literature is David F. Bradford, "Constraints on Government Investment Opportunities and the Choice of Discount Rate," The American Economic Review, Vol. LXV, No. 5, December 1975, pp. 887-899.

uncertainty. That being the case, both "high" and "low" estimates will be used as inputs to the least-cost computations in an attempt to assess the sensitivity of this uncertainty.

C. Center Capital Costs

The first cost element to be considered is depreciation. As a point of departure, a recent DOT capital stock study recommended the following expression, based on an accelerated (declining balance) formula, for approximating depreciation charges:[3]

$$\text{Annual depreciation rate} = \frac{1.5}{\text{asset's estimated life}}$$

However, that same study proposed as an offset to the depreciation charge a "revaluation" rate based on annual changes in the price index for capital assets. The revaluation concept implicitly assumes the existence of a re-sale market for the assets in question,which may be a dubious assumption in the case of FAA structures and equipment. Consequently, what would seem to be both a reasonable compromise and a reasonable approach to cost estimation would be to exclude the revalutaion offset while reducing the depreciation charge through the use of a straight-line formula:

$$\text{Annual depreciation rate} = \frac{1.0}{\text{asset's estimated life}}$$

Implementing this approach with data contained in the same study on airport/airway asset lives,[4] the following depreciation charges were estimated:

Center Structures: .0400

Center Equipment: .0603

The 1974 distribution of ARTCC capital between structures and equipment was .845

[3]U.S. Dept. of Transportation, Capital Stock Measures for Transportation, December 1974, Vol. I., Chapt. 5, pp. 5-2, 5-3.

[4]ibid, pp. 3-38,3-40.

and .155 respectively.[5] Combining these numbers and the depreciation rates produced the following (weighted) depreciation cost estimate:

$$.0400(.845) + .0603(.155) = \$.0431$$

The maintenance component was estimated by first dividing the 1974 ARTCC maintenance payroll by the value of the capital stock:

$$\$116,921,000/\$1,218,457,000 = \$.0960$$

Investigation revealed approximately 63% of maintenance labor is directly associated with capital equipment,[6] thus the direct maintenance component was estimated as:

$$.63(\$.0960) = \$.0604$$

There remains the "return to capital" element discussed at length in V.B. above. The DOT capital stock study cited earlier used as the basis for this estimate the long-term Federal borrowing rate. To the extent that such a cost is in fact relevant, it represents an implicit monetary interest cost as opposed to a "social opportunity cost" as discussed in the literature on discounting.[7] That rate in 1974 was .0699.[8]

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[5]Obtained from the FAA-developed time series data.

[6]U.S. Department of Transportation, Federal Aviation Administration, Airway Facilities Sector Level Maintenance Staffing Criteria and Standards, August 8, 1973. The 63% figure was derived by averaging MMH/MO, for all the classes within the facility alpha codes ARTCC and CTRB and standardizing their totals. The residual portion of the maintenance costs, in this case 37%, is the environmental maintenance that services both the controllers and the equipment. In effect this maintenance cost is "fixed", thus not relevant to this analysis.

[7]There is something of a consensus among economists that the before-tax return on capital invested in the private sector is an appropriate rate of discount. See Circular A-94, Bureau of the Budget, "Discounting Rates and Procedures to be Used in Evaluating Deferred Costs and Benefits," June 26, 1969, revised May 1972.

[8]Source: Economic Report of the President, February 1975, Table C-58, p. 317.

Summarizing, the ARTCC unit capital cost was estimated as:

$$r_{\zeta} = \$.0431 + .0604 + .0699 = \$.1734$$

D. Tower Capital Costs

The same estimation concepts, procedures and data sources were used for towers as for centers. Depreciation rates were:

Tower Structures: .0320

Tower Equipment: .0932

The 1974 distribution of tower capital between structures and equipment was .485 and .515 respectively. The weighted depreciation cost estimate was:

$$.0320(.485) + .0932(.515) = \$.0635$$

Division of the 1974 tower maintenance payroll by the value of that year's capital stock produced the following:

$$\$50,116,000/\$520,092,000 = \$.0963$$

Data in the Maintenance Staffing Handbook suggest that approximately 71% of maintenance labor is directly associated with equipment and thus considered variable in the context of this study. The final maintenance charge was thus:

$$.71(\$.0963) = \$.0683$$

The .0699 "return to capital" rate was carried forward from the previous section. Collecting results,

$$r_{\tau} = \$.0635 + .0683 + .0699 = \$.2017$$

VI. LEAST-COST INPUT COMBINATIONS

The purpose of this section is to apply the preferred enroute and tower production functions described in Sections III and IV together with estimates of the unit costs of labor and capital from Section V to determine least-cost input combinations associated with various levels of ATC service demand. A secondary objective is to provide a summary and central reference for the preferred production functions. The calculation of least-cost combinations will be in accordance with the mathematical optimization procedure described below.[1]

A. Optimization Methodology

The analytic problem to be solved may be stated formally as follows: Select the combination of labor and capital which minimizes total cost for a specified level of output, given a production function describing alternative input combinations which will satisfy that output. Let:

w = annual cost of a man-year of direct labor

r = annual cost of a unit (dollar) of capital stock (6.1)

$\bar{Q}$ = the specified level of output

$f(L,K)$ = the production function

[1]The reference for this is C.E. Ferguson, op.cit., pp. 157-158.

We wish to minimize

$$wL + rK \tag{6.2}$$

subject to

$$\bar{Q} = f(L,K) \tag{6.3}$$

As a Lagrangian problem, this is:

$$\text{Minimize } C = wL + rK - \lambda\{f(K,L) - \bar{Q}\} \tag{6.4}$$

where λ is the Lagrange multiplier. Setting the first partial derivatives equal to zero, we obtain

$$\begin{aligned} w - \lambda\frac{\partial f}{\partial L} &= 0 \\ r - \lambda\frac{\partial f}{\partial K} &= 0 \end{aligned} \tag{6.5}$$

Simplifying the above and eliminating λ, the result is

$$\frac{w}{r} = \frac{\frac{\partial f}{\partial L}}{\frac{\partial f}{\partial K}} = \frac{MP_L}{MP_K} = MRS_{L \text{ for } K} \tag{6.6}$$

In words, this says that cost minimization is achieved by the input combination where the marginal rate of substitution of labor for capital, which is the ratio of the marginal product of labor to the marginal product of capital (ref. Section II.B), is equal to the ratio of the cost of labor to the cost of capital.

B. ARTCC Input Combinations

For both the centers and towers, there will be two sets of least-cost calculations. The first will compare present vs. "optimal" mixes of labor and capital, while the second will compute requirements at five year intervals out to the year 2000. The latter will be based on FAA forecasts of aviation activity for those periods.

1. Present Mixes

Three of the ARTCC cross-section functions seemed to be equally preferable. The first used total aircraft handled as the output measure; the second used the classes of aircraft handled, weighted by speed reciprocals; and the third employed the measure in which the "scale" and "interactive" factors are combined. These functions are summarized below:[2]

Total Aircraft Handled (3.3)

$$Q_1 = 399.7\, L^{.684} K^{.337} \tag{6.7}$$

Aircraft Handled, Speed-Reciprocal Weights (3.5)

$$Q_2 = .687\, L^{.727} K^{.361} \tag{6.8}$$

Scale Plus Interactive Factors (3.14)

$$Q_3 = 287.0\, L^{.694} K^{.403} \tag{6.9}$$

The output levels selected for the least-cost calculations were those for a representative facility in the data base; i.e., the sample means. The relevant input data and results are presented below.

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[2] The multiplicative constant term is equal to the anti-log of $(\ell n \hat{a}_0 + \hat{\sigma}_u^2/2)$. The term $\hat{\sigma}_u^2/2$, which is estimated by one-half the square of the S.E.E., represents the correction for the problem mentioned in Section II. G p. 13, and discussed in the reference cited in footnote #7 on that page.

LEAST-COST VS. PRESENT (SAMPLE MEAN) MIXES

OF ARTCC LABOR AND CAPITAL

	Sample Means			Unit Costs		Least-Cost Mixes	
	Q	L	K*	w_ζ	r_ζ	L	K*
Function							
Q_1	974,687	438	$46,625	$22,286	$.1734	528	$33,449
Q_2	2,720	438	46,625	22,286	.1734	510	32,561
Q_3	1,537,382	438	46,625	22,286	.1734	514	38,376

*in thousands

Inspection of the above table leads to two observations. First, the three functions produce roughly equivalent results. Second, and perhaps more important, the present mix of labor and capital is decidedly different than the least-cost (LC) mix; i.e., there appears to be too much capital and too little labor. It should be emphasized that these results are highly sensitive to the labor and capital cost estimates and, in particular, to the inclusion of the "return to capital" component in the unit cost of capital. If that component is eliminated (reducing the center capital cost to $.1035) and the LC combination recomputed, the results are:

Function	Sample Means		Least-Cost Mixes	
	L	K	L	K
Q_1	438	$46,625	446	$47,263
Q_2	438	46,625	430	45,967
Q_3	438	46,625	425	53,191

The relationship between present and least-cost mixes is now much closer. In fact, using either of the first two functions, they are within 1-2% of each other. Thus, depending on which concept of capital cost (i.e., with or without "interest") policy analysts consider appropriate, these results suggest that the present ARTCC input combinations are either quite efficient or biased strongly in favor of capital and against labor.

2. Forecast Mixes

When considering future requirements for labor and capital based on forecasts of future levels of aviation activity, it is natural to think in terms of the ARTCC system as a whole. Thus the preferred time series function, constructed from aggregate data, is more appropriate than the cross-section functions. That function, from Eq. (3.20), is:

$$Q_t = .806\, L_t^{.681} K_{t-1}^{.328} \qquad (6.10)$$

with output measured in thousands of scale-interactive units. The FAA-supplied forecast data is given below.

ENROUTE ACTIVITY FORECASTS
(in millions of total aircraft handled)

Year	Air Carrier	Gen. Aviation	Military	$\sqrt{CG}$	$\sqrt{MG}$	Total
1975	12.9	7.3	4.3	9.7	5.6	39.8
1980	15.4	10.1	4.2	12.5	6.5	48.7
1985	17.1	17.0	4.3	17.0	8.5	64.0
1990	19.8	26.3	4.3	22.8	10.6	83.8
1995	22.2	32.3	4.3	26.8	11.8	97.4
2000	24.2	38.5	4.3	30.5	12.9	110.4

The least-cost input combinations required for the forecast output levels are shown in the following table. The labor figures appearing at the extreme right assume that capital is held constant at its 1974 levels for the subsequent years. The rationale behind this is, first, the LC capital requirement, computed from either the high or low capital input cost, is less than the actual 1974 level for the next several years. And, since decreases in capital stock tend to be both conceptually and administratively infeasible, it was considered to be of interest to compute the next decades' labor requirement associated with the fixed (1974) level of capital ($1.218 billion). It should also be noted that the methodology for determining least-cost input mixes relies on relative, and not absolute, input costs. Thus the use of 1974 labor and capital costs for forecast

purposes is consistent with that methodology, provided it is reasonable to assume that relative costs remain constant over time.

FUTURE ARTCC LEAST-COST INPUT COMBINATIONS

Year	Capital Cost = $.1734 Labor	Capital Cost = $.1734 Capital (thous.)	Capital Cost = $.1035 Labor	Capital Cost = $.1035 Capital (thous.)	Capital Constant @ $1.218 Billion Labor
1975	11,729	$ 726,029	9,917	$1,028,515	9,114
1980	14,320	886,423	12,108	1,255,735	12,250
1985	18,774	1,162,187	15,875	1,646,390	18,297
1990	24,543	1,519,273	20,753	2,152,249	27,210
1995	28,460	1,761,740	24,065	2,495,735	33,383
2000	32,233	1,995,306	27,255	2,826,613	40,744

C. Tower Input Combinations

1. Present Mixes

Production functions for Radar Approach, Approach Control, and Non-approach Control towers were developed in Section IV., Eq. Nos. (4.2), (4.7) and (4.9). They are:

$$Q_{RA} = 366.7\ L^{.737}K^{.425} \qquad (6.11)$$

$$Q_{AC} = 894.6\ L^{.775}K^{.352} \qquad (6.12)$$

$$Q_{NA} = 40.7\ L^{1.686}K^{.613} \qquad (6.13)$$

In the first two functions, output is defined as the sum of total operations, secondary instrument ops and overs. In the third, it is simply total ops. Data on present mixes (sample means), unit costs, and least-cost combinations are given below.

LEAST-COST VS. PRESENT (SAMPLE MEAN)
MIXES OF TOWER LABOR AND CAPITAL

Sub-Group	Sample Means			Unit Costs			LC Mix, r_{τ_1}		LC Mix, r_{τ_2}	
	Q	L	K*	w_τ	$r^{**}_{\tau_1}$	$r^{**}_{\tau_2}$	L	K*	L	K*
RA	212,219	44	$4458	20,889	$.2017	$.1318	53	$3190	46	$4179
AC	84,661	13	1358	20,889	.2017	.1318	17	800	15	1073
NA	131,393	10	893	20,889	.2017	.1318	13	480	11	656

*in thousands

**r_{τ_1} includes the return-to-capital component; r_{τ_2} does not.

As with the ARTC results, the least-cost mixes suggest a present deficiency of labor and excess of capital, except now the differences are more extreme. Note that relative to enroute control center costs, tower labor is less expensive and capital more expensive. Note also that even with the lower unit capital cost, the present mixes are still a difference of some 10% from "optimal" levels. There

is little else to be said about these results.

2. <u>Forecast Mixes</u>

Unfortunately, the effort to develop an adequate time series production function for towers did not prove successful. The forecast least-cost combinations must therefore be based on the cross-section functions. This is not an unreasonable approach, and it actually has some advantages over the use of a time series function. First, the most recent production technology is reflected in the cross-section function whereas a time series function of the form of (6.10) reflects a kind of "average" technology over a period of years. Second, given that the universe of towers consists of several sub-groups that are known to be qualitatively different, the separate cross-section functions provide an added degree of "structural integrity." The difficulty associated with their use in connection with aviation activity forecast data is that the forecast data tend to be quite aggregate in nature. It is therefore necessary to make several assumptions in order to convert those data to the required form, i.e., the output level of an average tower in each of the three sub-groups.[3] In this case, the following assumptions were made:

1) The distribution of total operations between RA, AC and NA towers (see footnote #3 below) will be the same as in 1974.

2) The number of towers in each sub-group will remain constant.

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[3]Another slight problem is that the tower forecasts are in terms of total operations. Two of the three production functions require total ops plus secondary instrument ops plus overs. In order to deal with this, once the forecast of total ops was distributed to the three sub-groups of towers, the RA and AC figures were increased by the 1974 ratio of secondary instrument ops and overs to total ops (.25 and .03 respectively.)

Neither of these assumptions is entirely realistic, but it is difficult to develop suitable alternatives. Assumption #2 is probably less realistic than #1, although the time series data on number of towers suggests a leveling off in the past few years. Given that each of the production functions admits of increasing returns to scale, the effect of underestimating future numbers of towers (and thus overestimating average output per tower) will be to underestimate aggregate labor and capital requirements through spurious realization of scale economies. Also worthy of consideration, however, is that the forecast number of towers is almost certainly as accurate as the forecast activity levels. The forecast data are given below.

AVERAGE TOWER OUTPUT FORECASTS
BY SUB-GROUP
(in millions)

Year	RA (158 towers)	AC (66 towers)	NA (214 towers)
1975	.193	.081	.149
1980	.246	.104	.190
1985	.363	.153	.280
1990	.498	.213	.385
1995	.600	.256	.463
2000	.703	.300	.542

Source: Aviation Policy Analysis Division, FAA

Once the labor and capital requirements for an average facility are computed, the aggregate requirements are obtained by multiplying the per-facility results by the number of facilities in each sub-group. The forecast least-cost mixes are:

FUTURE TOWER LEAST-COST INPUT COMBINATIONS

	Capital Cost = $.2017		Capital Cost = $.1318	
Year	L	K(in thous.)	L	K(in thous.)
1975	11,580	$ 624,052	10,128	$ 825,086
1980	14,168	756,556	12,186	999,712
1985	19,196	1,032,428	16,608	1,362,962
1990	24,392	1,334,154	21,106	1,760,552
1995	28,376	1,551,964	24,616	2,047,046
2000	32,268	1,765,814	27,754	2,328,700

Comparing these results with the outcome of the cross-section analysis and with the tower time series data, the aggregate labor requirements appear quite reasonable (1974 actual = 10,233). The capital requirements seem to be on the high side (1974 actual = $520,092), but that may instead confirm the existence of a problem with the tower capital stock series. The possibility of such a problem was first detected when the sample data on tower sub-groups was "blown up"

to estimate the aggregate capital stock. That estimate was substantially higher than the total capital reported in the time series. This matter should be reconciled before further analysis is conducted.

VII. CONCLUSIONS

The conclusions to be drawn from this study fall into two general categories, one pertaining to research or methodological issues and the other to policy implications. As for the former, although the overall feasibility of this type of research had been fairly well established in an earlier study, the present results provide even stronger evidence of the utility of econometric analysis in the context of air traffic control. Considerable progress has now been made in quantifying the relative importance of labor and capital for both center and tower operations, and in providing an analytic basis for assessing future resource requirements. On the less positive side, the issue of technological change remains elusive, and there is a certain "softness" in the capital cost estimates which precludes any unequivocal policy recommendations being made from these results.

With regard to policy matters, one of the primary contributions of this study is to focus attention on - and indeed, to provide empirical estimates of - the substitutability of labor and capital throughout the ATC system. It is apparent in retrospect that insofar as towers are concerned, the existence of trade-off possibilities between labor and capital can be observed from even the most casual inspection of the type of data analyzed here. Some towers with relatively little labor but extensive capital handle roughly the same levels and types of operations as others where inputs are used in reverse proportions. Centers on the other hand tend to have less flexible capital-labor mixes, although

enough variability can be found to permit meaningful estimation of the separate contribution of each.

Depending on which cost-of-capital concept is adopted (a subject discussed at great length in Section V), present resource combinations throughout the system appear to be either (1) quite efficient; or (2) somewhat overly capital intensive. The resolution of that controversy notwithstanding, the results here indicate that for both centers and towers, substantial additions to the net capital stock will be required if expansion of the system (to meet growing service demand) is to be economically efficient. In other words, requirements will exist for both new and replacement investment. The magnitudes of these various requirements are displayed in tables appearing in Section VI.

APPENDIX A

APPENDIX A

THE METHOD OF RIDGE REGRESSION

1. Background

Consider a matrix formulation of the general linear regression model:

$$Y = Xb + e \tag{A.1}$$

where

Y = n x 1 vector of observations on the dependent variable

X = n x p matrix of observations on the p non-stochastic independent variables

b = p x 1 vector of unknown parameters

e = n x 1 stochastic error term

On the assumption that

$$E(e_i e_j) = \begin{cases} \sigma^2 & \text{for } i = j \\ 0 & \text{for } i \neq j \end{cases} \tag{A.2}$$

i.e., that e has mean zero, constant variance and zero covariance, ordinary least squares (OLS) estimators of b,

$$\hat{b} = (X'X)^{-1}X'Y \tag{A.3}$$

are shown by the Gauss-Markov theorem to be best linear unbiased; that is, they have minimum variance <u>among the class of linear unbiased estimators</u>. While these are generally desirable properties, it is well to remember that the variance of the least squares estimators is highly dependent on the conditioning of X'X. If the vectors in X are closely interrelated, X'X will tend toward singularity and the <u>total variance</u>,

$$E(\hat{b} - E\hat{b})'(\hat{b} - E\hat{b}) = \sigma^2 \text{Trace}(X'X)^{-1} = \sigma^2 \sum_i (1/\lambda_i) \tag{A.4}$$

will be large since the smallest eigenvalue, λ_{min}, will be near zero. The consequences of this situation - often referred to as multicollinearity - have been demonstrated by Hoerl and Kennard[1] to be:

- Large estimation errors - This stems from the fact that, for unbiased estimators such as OLS, the mean square error of estimation, $E(\hat{b}-b)'(\hat{b}-b)$, is identically equal to the total variance of the estimators.
- Inflated values of the estimates - This can be seen from the fact that:

$$E(\hat{b}'\hat{b}) = b'b + \sigma^2 \sum_i (1/\lambda_i) \tag{A.5}$$

  In other words, the large variance property causes the average of the squared values of the parameter estimates to be considerably greater that the squared values of the true (but unknown) parameters.

- Instability of the estimates - This is another way of saying that the estimates are sensitive to small changes in the data base. It follows simply from interpreting the variance of an estimator as a measure of the degree to which estimates will take on different values from one sample to another.[2]

2. Ridge Estimators

Recognizing that the above can lead to quite unsatisfactory estimates of regression coefficients in many applied settings, Hoerl and Kennard[3] have proposed an alternative estimation procedure based on the idea of "deflating" the parameter estimates. Their derivation, which may be stated in the form of a Lagrangian problem, is as follows:

$$\text{Minimize } F = B'B + (1/k)\{(Y - XB)'(Y - XB) - \phi\} \tag{A.6}$$

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[1] "Ridge Regression: Biased Estimation for Nonorthogonal Problems," Technometrics, Vol. 12, No. 1, February 1970, pp. 55-67.
[2] A fourth consequence they allude to but provide no analytic demonstration of is that some of the estimates may have implausible algebraic signs.
[3] Op.Cit.

A verbal interpretation of this is to minimize the sum of squares of the estimates (the elements of the vector B), subject to a side condition which places a limit on the amount by which the residual sum of squares may exceed the minimum (OLS) value. The expression in brackets is the side condition with ϕ = total (minimum plus incremental) residual sum of squares, and (1/k) is the Lagrange multiplier. Setting $\partial F/\partial B = 0$, they obtain:

$$B = \hat{\beta}^* = (X'X + kI)^{-1}X'Y \qquad \text{(A.7)}$$

In this expression I is the identity matrix and X'X and X'Y are understood to be in correlation form, thus reducing all dimensions from p to p-1. $\hat{\beta}^*$, which Hoerl and Kennard term the ridge estimator because of its mathematical similarities with the portrayal of quadratic response functions, parallels a vector of "beta" coefficients in standard regression theory. Conversion to estimates of regression coefficients is performed by:

$$\hat{b}_i^* = \hat{\beta}_i^* \, \sigma_y/\sigma_{x_i} \qquad \text{(A.8)}$$

The intercept term, $\hat{b}_o^*$, is computed from:

$$\hat{b}_o^* = \overline{Y} - \sum_i \hat{b}_i^* \, \overline{X}_i \qquad \text{(A.9)}$$

The formal procedure outlined above requires that ϕ be specified initially. This then implies a value for k. However, in applications of Ridge estimation, Hoerl and Kennard recommend examination of several values of k in the interval {0,1}, and that the preferred $\hat{\beta}^*$ be chosen to correspond to the value of k where the estimates begin to stabilize. They suggest a graph, called the Ridge Trace, of $\hat{\beta}_i^*$ as a function of k as a visual means of identifying the point (or range) where stability occurs. In the example Trace shown in Figure 1, stabilization takes place in the

neighborhood of $k = .3$, and the estimates corresponding to that value are the preferred ones. At the bottom of the graph, SSE/TSS is a plot of the residual sum of squares, i.e., $SSE/TSS = (1-R^2)$.

3. Comparison of Ridge and OLS

An interpretation of (A.7) above is that for $k = 0$, Ridge and OLS are identical. The consequences, from an analytic point of view, of moving to $k > 0$ is to reduce the variance of the estimators at the expense of introducing bias. A natural question arising at this point is what is the net effect of such a move. It is easily shown that if $\hat{\theta}$ is an estimator of the scalar Θ, then

$$E(\hat{\Theta} - \Theta)^2 = E(\hat{\Theta} - E\hat{\Theta})^2 + (E\hat{\Theta} - \Theta)^2 \tag{A.10}$$

That is, the mean square error of estimation decomposes into the variance of the estimator plus the square of its bias. An analogous result holds for vectors. Hoerl and Kennard have shown the mean square error function for Ridge to be:

$$\begin{aligned} E(\hat{\beta}^* - \beta)'(\hat{\beta}^* - \beta) &= \sigma^2\Sigma\lambda_1/(\lambda_1 + k)^2 + k^2\beta'(X'X + kI)^{-2}\beta \\ &= \gamma_1(k) + \gamma_2(k) \end{aligned} \tag{A.11}$$

The first component, $\gamma_1(k)$, is the total variance of the estimates, and the second, $\gamma_2(k)$, is the square of the bias introduced when $\hat{\beta}^*$ is used rather than $\hat{\beta}$. An interesting feature of this function is that the derivative of $\gamma_1(k)$ in the neighborhood of the origin is negative, while the derivative of $\gamma_2(k)$ is zero there. In Hoerl and Kennard's words, "These properties lead to the conclusion that it is possible to move to $k > 0$, take a little bias, and substantially reduce the variance, thereby improving the mean square error of estimation and prediction."[4] They also prove an existence theorem to validate this conclusion.

[4]Ibid, p. 61

EXAMPLE RIDGE TRACE

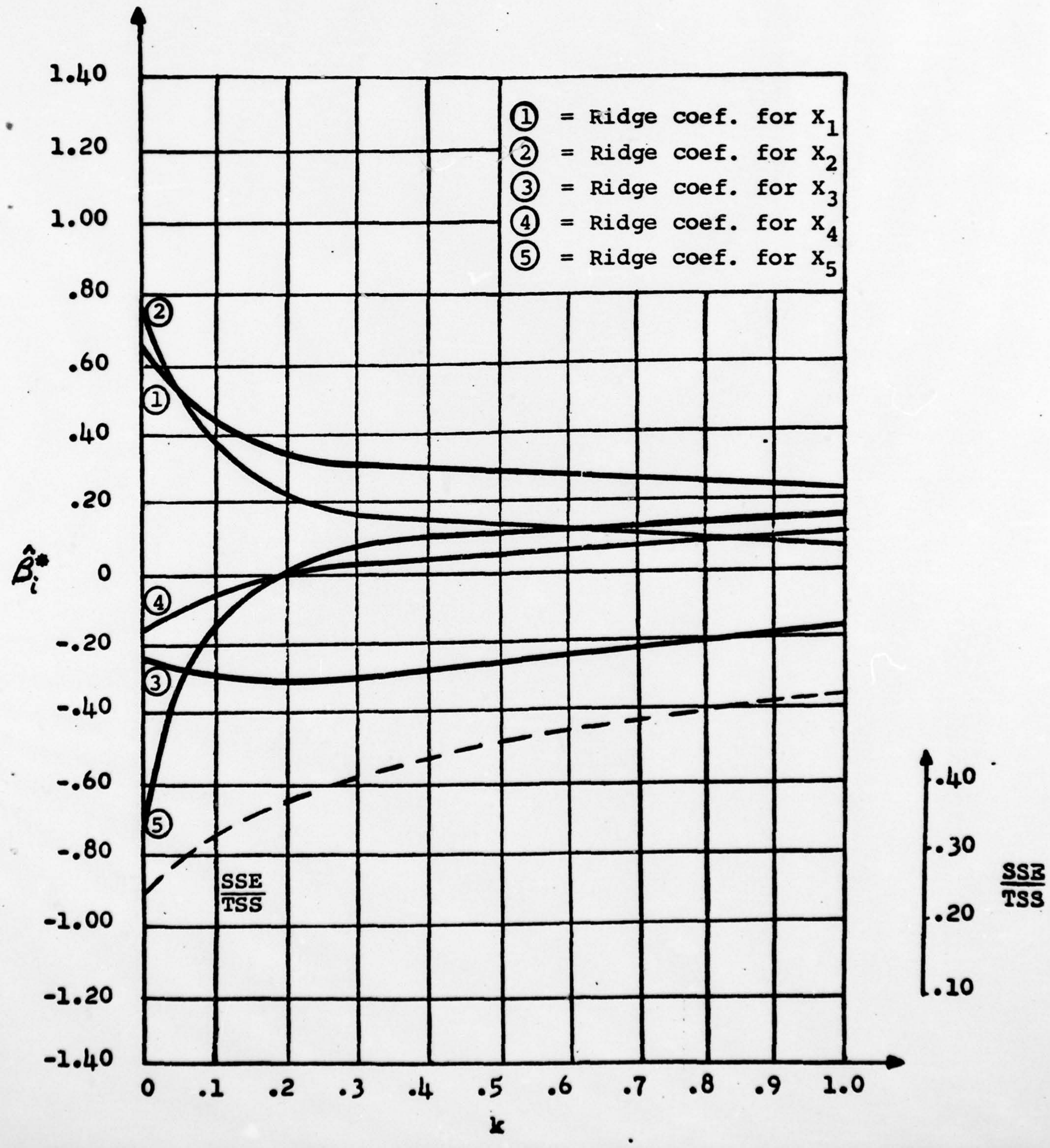

FIGURE 1

APPENDIX B

APPENDIX B

This appendix contains the data bases[1] used to derive the production functions presented in the body of this report.

Aircraft operations data were taken from FAA Air Traffic Activity documents. Direct labor statistics were supplied by the FAA Office of Personnel and Training (APT-20). The capital stock figures for both the ARTCC and the tower time series were derived from annual investment and expenditure data. Efficiency depreciation procedures[2] were applied to estimates of undepreciated value of capital stock using the age distribution of the physical facility inventory to provide capital stock cross section data.

In addition to these standard measures, Table B-1 lists the air speed interactive factors ($\sqrt{C\ G}$, $\sqrt{M\ G}$), the airspeed weighted total operations, and available measures of potential conflicts avoided[3], for all ARTCC's.

Table B-2 contains the time series data for the ARTCC's.

Table B-3 thru B-5 describe the data for towered airports, categorized as radar approach control, approach control, and non-approach control facilities respectively.

Table B-6 lists those of the largest towers for which runway acceptance rates[4] were available.

Table B-7 contains the time-series data for tower facilities.

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[1]The source of this data was the Aviation Policy Analysis Division (AVP-210), Federal Aviation Administration.

[2]<u>Capital Stock Measures for Transportation</u>, Jack Faucett Assoc., Inc., December, 1974.

[3]<u>Air Traffic Control Productivity Trends,</u> Office of Aviation Policy, Federal Aviation Administration, forthcoming in 1976.

[4]<u>Impacts of UG3RD Implementation on Runway System Delay and Passenger Capacity</u>, Battelle Columbus Labs, March 31, 1976.

TABLE B-1

ARTCC CROSS-SECTION DATA

Center	Total A/C Handled	Air Carrier Handled	Air Taxi Handled	Gen. Aviat. Handled	Military Handled	Dir. Lab. (Man-Yrs)	Total Capital Stock (deprec.) (Thous of '74$)
Anchorage, AK	194,307	115,683	11,828	24,467	42,329	143	26,482
Los Angeles, CA	1,021,366	609,233	21,549	124,395	266,189	450	54,833
Oakland, CA	892,259	474,136	21,940	112,380	283,803	438	47,507
Denver, CO	633,828	434,323	12,710	87,210	99,585	368	52,997
Washington, DC	1,337,928	754,918	24,657	312,488	245,865	613	39,788
Jacksonville, FL	1,063,371	485,006	26,004	240,678	311,683	526	49,435
Miami, FL	1,026,769	634,823	77,207	195,873	118,866	401	41,007
Atlanta, GA	1,409,660	805,484	10,751	394,617	198,808	621	45,455
Honolulu, HI	374,180	269,789	756	4,449	99,186	143	21,850
Chicago, IL	1,659,629	956,692	139,221	497,352	66,364	687	56,375
Indianapolis, IN	1,263,802	619,821	84,570	440,953	118,458	548	43,243
Boston, MA	913,850	481,014	79,770	193,107	159,959	491	45,626
Minneapolis, MN	925,770	511,131	55,575	238,237	120,827	408	48,323
Kansas City, MO	999,889	486,130	62,048	280,535	171,176	479	53,426
Great Falls, MT	191,087	98,445	6,280	28,350	58,012	59	24,075
Albuquerque, NM	862,518	327,003	936	79,263	455,316	400	59,314
New York, NY	1,529,768	1,045,210	70,647	314,786	99,125	705	50,324
Cleveland, OH	1,645,299	971,401	111,754	486,715	75,429	693	55,119
Memphis, TN	1,092,182	486,801	42,124	287,562	275,695	448	46,868
Ft. Worth, TX	1,242,066	568,512	47,365	242,724	383,465	468	47,919
Houston, TX	1,098,370	426,783	44,695	246,452	380,440	479	56,987
Salt Lake City, UT	407,988	258,718	10,412	57,050	81,808	243	55,490
Seattle, WA	631,862	283,857	40,901	166,495	140,609	256	49,932

TABLE B-1 (CON'T)

ARTCC CROSS-SECTION DATA

Center	$\sqrt{G\,C}$ [1]	$\sqrt{G\,M}$ [1]	Weighted A/C OPS	Conflict Avoidance Measures
Anchorage, AK	64,797	39,196	298,300	-
Los Angeles, CA	298,184	197,100	1,516,650	723.24
Oakland, CA	252,360	195,244	1,339,863	658.88
Denver, CO	208,320	99,752	941,900	1,415.98
Washington DC	504,496	287,909	2,130,333	3,700.25
Jacksonville, FL	359,642	288,305	1,711,318	1,855.33
Miami, FL	416,362	180,166	1,623,297	1,353.53
Atlanta, GA	571,417	283,884	2,264,961	1,057.15
Honolulu, HI	37,473	22,721	434,374	-
Chicago, IL	780,387	205,537	2,645,553	2,489.04
Indianapolis, IN	570,727	249,504	2,084,033	2,027.35
Boston, MA	362,294	208,923	1,485,067	1,247.46
Minneapolis, MN	387,526	188,415	1,501,711	583.98
Kansas City, MO	408,092	242,161	1,650,142	1,814.83
Great Falls, MT	81,347	44,821	317,255	-
Albuquerque, NM	161,942	191,091	1,215,551	831.71
New York, NY	634,711	195,463	2,359,942	4,567.01
Cleveland, OH	762,465	212,466	2,620,230	5,611.09
Memphis, TN	400,613	301,484	1,794,279	1,385.04
Ft. Worth, TX	406,102	333,525	1,981,693	284.70
Houston, TX	352,500	332,812	1,783,682	1,623.05
Salt Lake City, UT	132,112	74,289	614,389	-
Seattle, WA	242,633	170,768	1,045,263	-

[1] Airspace Interactive Factors

TABLE B-2

ARTCC TIME SERIES DATA

Year	Total A/C Handled (000)	Air Carrier Handled (000)	Gen. Aviation (incl. Air Taxi) Handled (000)	Military Handled	Dir. Lab. (Man-Yrs)	Total Capital Stock (deprec.) (Thous of '74$)
45	2,139	-	-	-	618	100,755
46	2,292	-	-	-	779	112,154
47	2,619	-	-	-	846	132,482
48	2,236	-	-	-	1,108	146,404
49	2,301	-	-	-	1,255	152,933
50	2,608	-	-	-	1,264	160,487
51	3,064	-	-	-	1,428	166,270
52	3,416	-	-	-	1,386	167,430
53	3,907	-	-	-	1,513	167,315
54	4,385	-	-	-	1,575	165,749
55	5,377	-	-	-	1,837	167,011
56	6,552	-	-	-	2,196	167,262
57	8,023	4,521	503	2,999	3,329	235,836
58	9,009	4,735	536	3,739	4,092	294,141
59	9,735	5,346	585	3,804	6,463	347,493

TABLE B-2 (Con't)

ARTCC TIME SERIES DATA

Year	Total A/C Handled (000)	Air Carrier Handled (000)	Gen. Aviation (incl. Air Taxi) Handled (000)	Military Handled	Dir. Lab. (Man-Yrs)	Total Capital Stock (deprec.) (Thous of '74$)
60	9,438	5,272	678	3,488	6,804	431,550
61	9,697	5,296	792	3,609	6,443	530,738
62	10,056	5,332	920	3,804	6,253	572,800
63	10,602	5,566	922	4,115	6,381	619,712
64	11,683	5,966	1,108	4,609	6,591	658,729
65	12,859	6,827	1,480	4,552	6,437	658,005
66	14,096	7,757	2,021	4,317	6,428	653,042
67	16,630	9,786	2,469	4,375	6,179	712,402
68	19,383	11,807	2,963	4,613	7,218	771,043
69	21,571	13,352	3,473	4,746	8,556	848,838
70	21,405	13,215	3,706	4,484	10,130	1,000,437
71	21,683	12,657	4,247	4,779	10,892	999,697
72	22,063	12,316	5,061	4,685	10,365	1,131,655
73	23,349	12,823	5,897	4,628	10,155	1,207,279
74	23,049	12,222	6,485	4,342	10,242	1,218,457

TABLE B-3

RADAR APPROACH CONTROL

TOWER CROSS-SECTION DATA
(Original Sample)

Tower	Total A/C Operations*	Direct Labor (Man-Years)	Total Capital Stock (deprec.) (Thos. of '74$)
Chicago O'Hare, IL	806,588	145	11,250
San Antonio Int., TX	439,045	90	5,153
Columbus Int., OH	367,745	72	5,184
Charlotte, NC	211,886	52	4,324
Columbia, SC	151,088	34	4,417
Montgomery Danelly, AL	160,505	44	1,503
West Palm Beach, FL	215,124	39	4,254
Lincoln Municipal, NE	204,427	20	4,598
Fort Wayne, IN	155,708	37	4,106
South Bend, IN	165,548	38	4,436
Lexington, KY	124,654	28	3,568
Fort Smith Muncipal, AR	95,271	18	4,721
Wilkes-Barre, PA	94,524	19	3,209

* Includes Instrument Secondarys and Overs

TABLE B-3 (Con't)

RADAR APPROACH CONTROL
TOWER CROSS-SECTION DATA
(Additional Sample)

Tower	Total A/C Operations*	Direct Labor (Man-Years)	Total Capital Stock (Deprec.) (Thos. of '74$)
Roanoke, VA	140,411	34	4,587
Madison, WI	198,866	27	4,359
Burlington, VT	150,897	44	3,062
Sioux Falls, SD	92,089	11	5,564
Chattanooga, TN	142,245	32	3,981
Monterey, CA	107,802	21	4,582
Albany, NY	151,350	43	4,591
Swanton, OH	207,800	36	4,044
Portland, OR	211,221	52	4,255
Birmingham, AL	223,490	52	3,623
Albuquerque, NM	228,559	50	3,737
Burbank, CA	258,617	51	4,350

*Includes Instrument Secondarys and Overs

TABLE B-4

APPROACH CONTROL

TOWER CROSS-SECTION DATA

Tower	Total A/C Operations*	Direct Labor (Man-Years)	Total Capital Stock (Deprec.) (Thos. of '74$)
Lafayette, LA	145,213	22	1,395
Wilmington, NC	119,880	15	1,312
Gulfport, MI	105,353	14	1,080
Muskegon, MI	86,163	15	1,358
Hutchison, KS	74,718	11	1,179
Lynchburg, VA	73,026	11	1,275
Bismarck, ND	65,668	12	1,748
Waco, TX	65,889	15	1,181
Pendleton, OR	55,418	10	1,614
Grand Junction, CO	57,117	10	1,293
St. Joseph, MO	82,825	12	1,499

*Includes Instrument Secondarys and Overs

TABLE B-5

NON-APPROACH CONTROL

TOWER CROSS-SECTION DATA

Tower	Total A/C Operations	Direct Labor (Man-Years)	Total Capital Stock (Deprec.) (Thos. of '74$)
Pontiac, MI	249,154	14	901
Bridgeport, CT	166,380	13	674
Plainview, TX	48,985	7	449
Lancaster, PA	153,627	8	1,358
Santa Rosa Sonoma Co., CA	146,744	12	835
Modesto City County, CA	132,043	9	1,198
Fresno Chandler, CA	90,080	10	549
Westfield, MA	133,559	11	984
Appleton, WI	61,969	8	1,088

TABLE B-6

RUNWAY ACCEPTANCE RATE

TOWER CROSS-SECTION DATA

Tower	Total A/C Operations*	IFR**	VFR**	Direct Labor (Man-years)	Total Capital Stock (Deprec.) (Thos. of '74$)
Chicago O'Hare, IL	806,588	102	137	145	11,250
Atlanta, GA	586,003	108	130	146	7,938
Miami, FL	497,805	101	116	122	6,286
Washington National, DC	454,310	54	62	103	5,167
Boston, MA	376,946	52	92	80	5,384
Denver, CO	430,291	52	60	77	8,406
Pittsburg Greater, PA	357,824	82	101	78	5,315
Detroit Wayne, MI	399,508	79	117	85	5,189
St. Louis International, MO	394,476	59	76	80	6,572
Philadelphia, PA	409,407	57	73	97	4,994
Minneapolis St. Paul, MN	298,034	58	89	67	5,856
Cleveland, OH	344,780	52	73	76	5,629
Dallas-Ft.Worth, TX	230,540	130	145	118	8,548
Houston, TX	350,910	83	97	81	6,377
Memphis, TN	321,451	93	142	78	6,596
Tampa, FL	324,972	82	118	82	5,174
Honolulu, HI	336,718	52	66	60	5,146
Seattle-Tacoma Int'l., WA	242,324	54	68	63	7,258
Kansas City Int'l. MO	245,725	89	101	67	7,847
New Orleans-Moisant, LA	206,476	56	65	60	4,656
Las Vegas, NV	284,543	81	91	53	4,017
Indianapolis, IN	257,442	62	77	66	5,761
Covington Gr. Cinn., KY	203,024	55	67	58	6,040
JFK International, NY	380,816	59	81	49	7,076
San Francisco, CA	341,516	52	77	95	3,416
La Guardia, NY	386,541	59	73	46	2,542
Dallas Love, TX	368,577	58	93	22	2,565
Newark, NJ	234,731	54	69	42	5,702
Los Angeles, CA	548,676	107	167	101	9,951
Phoenix, AZ	627,596	58	118	59	5,111

*Includes Instrument Secondarys and Overs
**Runway Acceptance Rates

TABLE B-7

TOWER TIME SERIES DATA

Year	Total Operations (000)	Direct Labor (Man-Years)	Total Capital Stock (deprec.) (Thous of '74$)
45	9,252	31	21,260
46	11,927	50	25,593
47	17,670	1,166	33,213
48	18,378	1,516	38,578
49	16,940	1,785	41,151
50	15,971	1,784	44,180
51	17,026	1,794	46,611
52	15,814	1,740	47,179
53	16,815	1,986	47,115
54	17,945	2,068	46,272
55	19,488	2,114	46,210
56	22,046	2,303	44,192
57	25,150	3,345	44,966
58	26,593	3,898	77,736
59	26,906	4,888	90,477
60	25,774	5,337	105,337
61	26,301	5,562	118,376
62	28,201	5,741	134,978
63	30,977	6,146	153,685
64	34,195	6,111	192,677
65	37,871	6,258	207,141
66	44,953	6,146	224,783
67	49,887	6,099	247,395
68	55,292	6,803	267,493
69	56,232	7,503	297,000
70	55,280	8,429	306,738
71	53,702	9,082	381,776
72	53,256	9,247	463,071
73	56,554	9,718	497,729
74	57,534	10,233	520,092